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OPTICALLY-AMPLIFIED SCALABLE WDM NETWORKS USING ACOUSTO-OPTIC FILTERS FOR AMPLIFICATION GAIN EQUALIZATION AND SIGNAL ROUTING

Case Western Reserve University

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OPTICALLY AMPLIFIED SCALABLE WDM NETWORKS USING ACOUSTO-OPTIC FILTERS FOR AMPLIFICATION GAIN EQUALIZATION AND SIGNAL ROUTING

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13. ABSTRACT *(Maximum 200 words)*

This final report discusses development of Acousto-Optic Tunable Filter (AOTF) technology for wavelength-division multiplexing (WDM) in optical networks. The ability of the AOTF to function as a digital or analog wavelength-selective filter, with independent control of each wavelength channel or spectral window allows the AOTF to solve the seemingly unrelated problems of gain equalization and wavelength channel routing simultaneously. An AOTF with intrinsic gain also provides the capability for a lossless switch. Specific results of the effort include: packaged sidelobe-suppressed AOTF's as hybrid polarization-independent switches for gain equalization experiments, requirements for passive and active filters for effective gain equalization in single and cascaded Erbium Doped Fiber Optic Amplifiers, single amplifier cascades, delivery of a gain equalizer subsystem to ONTC, the development of a mathematical model for AOTFs with gain, fabrication of waveguides in Er:Ti:LiNb03, requirements for optimum pump and device packaging of AOTFs with gain, demonstration of the gain and noise properties of AOTFs with gain, and determination of optimal system performance of an AOTF with gain.

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Introduction

It has been predicted for some time that future transparent optical networks will incorporate wavelength-division multiplexing (WMD) to achieve the necessary high network capacity. WDM technology allows independent channels to be simultaneously transmitted on different wavelengths. Not only does this offer a significant increase in capacity but also a richer range of connection possibilities than is achievable in single-wavelength communication systems. Erbium-doped fiber-optic amplifiers (EDFAs) play an essential role in the development of these systems because they compensate for fiber attenuation and signal distribution losses.

There are two critical system problems that must be addressed in these WDM networks. Firstly, robust components must be developed for wavelength-selective access and routing which can handle a wide dynamic range in system variables. These optical access nodes must be able to inject a channel, remove a previously injected signal, recover the data on another wavelength and to reduce rather than exacerbate the problem of gain non-uniformity.

The second issue is the non-uniform gain across the EDFA spectrum. There is a critical need for a cost-effective, robust technique for automatic equalization of the amplifier gain. This is needed to maintain uniform signal-to-noise ratios among many WDM channels along an amplifier chain. Passive compensation of the EDFA gain profile is unacceptable since the gain profile is a dynamic function, and will vary on a millisecond time scale in a multi-user network.

Because of its ability to function as a digital or analog wavelength-selective filter, with independent control of each wavelength channel or spectral window, the AOTF can be used to solve the seemingly unrelated problems of gain equalization and wavelength channel routing simultaneously. A further extension of the AOTF device performance is an AOTF with intrinsic gain to provide a loss-less switch. These devices may be particularly important where implementing EDFAs will be impractical, such as in large switch matrices. This program undertook the next exploratory step of investigating the doping of an AOTF with Er to provide gain.

Description of Scope of Work

The deliverables are broken up into two parts; equalizer projects (E1-E5) and AOTF with gain projects (G1-G4).

Project #1: Equalizer projects
E1: Package sidelobe-suppressed AOTFs as hybrid polarization-independent switches for gain equalization experiments (Li).
E2: Determine passive and active filter requirements for effective gin equalization in single and cascaded EDFA chains in WDM systems (Willner).
E3: Perform single amplifier equalization experiments in open and closed loop (Smith/Willner).
E4: Demonstrate dynamic equalization in amplifier cascades (Willner).
E5: Deliver gain equalizer subsystem to ONTC or other testbed for evaluation (Smith/Willner/Li).

Project #2 AOTFs with Gain
G1: Develop mathematical model of AOTFs with gain (Smith).
G2: Make waveguides in Er:Ti:$LiNbO_3$ using local vendor facilities (Li) .
G3: Determine optimum pump and device packaging requirements for AOTF with gain (Li).
G4: Demonstrate gain and noise properties of AOTF with gain (Willner/Smith).
G5: Determine optimal system performance of an AOTF with gain (Willner).

Project #1: Package sidelobe-suppressed AOTFs as hybrid polarization-independent switches for gain equalization experiments

The AOTF is a versatile device with many potential advantages in optical systems. However, as in many other state-of-the-art devices, there are several issues which complicate its use in practical systems. These issues include robustness, packaging, insertion loss, and insensitivity to input polarization and temperature.

E1a: Make unpackaged AOTF

Four single-polarization AOTFs were fabricated using the apodized design of the model #4511 AOTF manufactured by New Focus Inc. Two devices were delivered to D. Smith at CWRU and another two devices were delivered to A. Willner at USC. The devices were delivered in November 1994 to allow initial experiments in amplifier gain equalization to begin.

Focused Research was able to benefit from investigations carried out by New Focus into the robustness and packaging of the model #4511 AOTF. Tests were performed at the Jet Propulsion Laboratories to determine the suitability of the devices for such harsh environments such as space flight. The results showed that the devices survived the vibration and temperature tests and demonstrated that the New Focus packaged AOTFs would be suitable for practical systems integration.

E1b&c: Packaged polarization insensitive AOTFs for D. Smith and A. Willner
In parallel with the fabrication of single-polarization AOTFs, a hybrid scheme was designed to produce AOTFs which were polarization-independent. The final design is shown in Figure 1 and consists of two four-port polarization splitters, two single-polarization AOTF modules, and eight fiber collimators connected to polarization maintaining (PM) fiber. Input light enters the system via Input 1 or Input 2. The polarization components then travel to their respective filters and are recombined after the second polarization beamsplitter. The unfiltered output of Input 1 and the filtered output of Input 2 exit through one fiber while the filtered output of Input 1 and the unfiltered output of input 2 exit through the second fiber output. The hybrid system was based upon the New Focus rail system . This enabled matching of each leg length to within a few millimeters, which is crucial for maintaining low bit error rates. In designing this system, a beamsplitter mount was developed and New Focus introduced a similar mount as a new product in their 1995 catalog.

The first AOTFs delivered to D. Smith and A. Willner were returned to Focused Research and incorporated into the hybrid polarization-insensitive package. The packaged hybrid devices were then shipped to D. Smith and A. Willner in February 1995 for further investigation of gain equalization.

E1d&e: Thermoelectrically cooled AOTFs for D. Smith and A. Willner
Results from the experiments performed on the hybrid system by D. Smith and A. Willner prompted several modifications to be made to the design of the polarization-insensitive AOTF modules. The most significant change was the incorporation of thermoelectric (TE) coolers in the modules. The design of the new device package is shown in Figure 2. The temperature controlled AOTFs in the hybrid design were needed to provide temperature stabilization of the device. New devices were also needed because the earlier hybrid device had shown wavelength dependent crosstalk. This was attributed to the misalignment of the PM fiber axes relative to the crystal axes of the AOTF substrates, and to the misalignment between PM fibers themselves. This misalignment between polarization axes caused birefringence beating. Therefore, in the later temperature controlled versions extreme care was paid to the orientation of the fibers in the pigtailing process. Focused Research delivered two TE cooled AOTFs to D. Smith in November 1995 and another two to A. Willner in December 1995.

Project #2 AOTFs with Gain

One of the major criticisms against AOTFs and ferroelectric waveguide technology in general is the relatively high insertion loss. To overcome this limitation we proposed a novel effort to develop a loss less switch device which would obviate the need for separate fiber amplifiers. The gain in the device would be provided by Er dopants introduced into the $LiNbO_3$ host material. The Focused Research effort was split into two

areas; 1) the investigation and optimization of the fabrication processes required to create Er doped AOTFs and 2) evaluation of efficient pumps and a study of gain and loss as a function of pump wavelength and power. A theoretical study of the filter transmission function in a pumped AOTF waveguide was carried out in parallel with the device fabrication, and once the devices were complete they were shipped to the other members of the consortium for experimental investigation and comparison with the theoretical models.

G2: Make waveguides in Er:Ti:$LiNbO_3$ using local vendor facilities.
In order to determine the optimum diffusion process for doping $LiNbO_3$ with erbium, a thorough investigation into different process conditions was conducted. A comparison was made between the diffusion of thin (10 nm) erbium metal films and thick (100nm) erbium oxide films into X-cut and Z-cut $LiNbO_3$. The environment in which the diffusion takes place is critical to the process and especially for maintaining the appropriate Li concentration. The sample was placed in an Al_2O_3 boat containing lithium niobate powder and was mounted on a piece of platinum foil. The temperature range investigated was limited to 1140°C by the Curie temperature of $LiNbO_3$. Tests were also carried out on pure lithium niobate as control samples.

SIMS analysis was performed to investigate the diffusion of erbium into $LiNbO_3$ as a function of diffusion time. Figure 3 shows the erbium concentration versus depth into the crystal for samples diffused with 11 nm of erbium at a temperature of 1100°C. The concentration at the surface after 100 hours diffusion was 1.27×10^{20} atoms/cm^3. The diffusion constant was determined from the FWHM to be 7.3×10^{-14} cm^2/s (independent of diffusion time), which corresponds to 0.67 mole % at the surface.

The samples were also inspected under a high power optical microscope. Figure 4 shows optical micrographs taken of the samples. The micrographs clearly shows the disruption of the surface quality by microcrystallites of secondary phase compounds for lower diffusion temperatures (1100°C) and the oxide layers. Interestingly, the diffusion profile in Figure 3 shows a small peak in the erbium concentration at the surface, which corresponds to the formation of microcrystallites at the surface at 1100°C. The optical micrographs indicated that the optimum erbium diffusion conditions were 1135°C for 100 hours using 11 nm of erbium metal.

Once the $LiNbO_3$ had been successfully doped with Er without disrupting the surface properties, waveguides were created using Ti diffusion. The first experiments used the standard Ti diffusion conditions to create waveguides. A 100 nm thick film of Ti was lithographically patterned with strips of various widths to form channel waveguides. The Ti was then diffused into the Er:$LiNbO_3$ for 9 hours at 1025°C.

Optical characterization of the waveguides showed that at a wavelength of 1.5 μm, the waveguides were single-mode for channel widths between 6 and 10 μm. The tests also showed that the optical propagation loss was very high (>5 dB/cm). This could have been due to high scattering loss, but one would also expect unpumped Er doped substrates to

be absorbing at 1550 nm. These waveguides were therefore tested in the pumping experiments which will be described in the next section.

The results from the pumping experiments conducted in parallel with the fabrication investigation, led us to reinvestigate the diffusion conditions in light of the possible interaction of the Ti and Er in the host material The Ti diffusion experiments were repeated at higher temperatures to investigate the effect of temperature on the surface structure. As we discussed in our original proposal, we intended to have the AOTF devices fabricated at a US foundry such as UTP rather than the British foundry used by New Focus. The conditions which were investigated included those used by UTP to create undoped AOTF devices - 1050°C for 8 hours. Figure 5 shows optical micrographs of the surface quality produced at various temperatures. The results showed that a temperature of 1065°C for 8 hours was necessary to avoid the formation of secondary phase compounds at the surface. This meant that standard fabrication techniques would not be possible and the devices would need to be custom processed at New Focus and other local vendors

G3: Determine optimum pump and device packaging requirements for AOTF with gain.

Optimum Pumping Requirements for AOTFs with Gain

Prior to the delivery of a finished Er doped AOTF device to D. Smith and A. Willner (for them to determine gain properties), an investigation of pump requirements was performed at Focused Research. The main goals of this investigation were to verify that the waveguides would indeed produce gain and to determine the level of pumping required. The experimental arrangement used to measure the gain is shown in Figure 6. A New Focus external cavity tunable diode laser, model #6262, was used to provide continuously tuning of the signal wavelength. This allowed us to compare the gain spectra in our Er doped lithium niobate samples with spectra already published in the literature.

The output of the tunable laser was coupled into polarization maintaining fiber via a waveplate which could be rotated to optimize coupling efficiency. The pump laser used was an AT&T type 255 laser operating at 1480 nm with a maximum output power of 60 mW. The signal was combined with the pump laser by means of a WDM coupler. A system of collimating and focusing optics were used to mode match the beam and launch the combined signal and pump lasers into the waveguide. At the output of the waveguide the signal and pump lasers were separated using a grating and monitored with a New Focus model #2011 photodetector. For this investigation the waveguide was not fiber pigtailed and therefore losses in the optical system were large. Consequently, the measured power level of the pump laser at the input of the waveguide was only 6.2 mW.

Results of the experiment showed that, even with the relatively low launched pump power, the gain in the waveguide was measured to be 3.4% (0.2 dB) and 9.8% (0.4 dB) at signal wavelengths of 1525nm and 1550nm respectively. This decrease in gain at lower

wavelengths is in agreement with the gain spectrum for Er in LN described in Ref. (1). The low gain measurements can be attributed in part to the high insertion loss of 5 dB. This loss included the absorption of the Er, but also a large contribution from scattering caused by surface roughness resulting from the waveguide fabrication process. The results of this test led us to perform further studies of the Ti diffusion process to reduce the waveguide insertion loss which are described in the section above.

These pumping experiments confirmed that 1480nm was a suitable pump wavelength and that the 80mW laser identified for the investigation provided sufficient pump power to achieve gain in the Er, even with the relatively low coupling efficiency.

Device Fabrication and Packaging of AOTFs with Gain.

Our results for the investigation of diffusion conditions showed that micro-crystallites were formed during Ti diffusion at temperatures between 1025°C and 1060°C. This temperature range covers the temperatures currently used by New Focus Inc. and UTP to process commercial AOTFs. Because the UTP process was incompatible with low-loss Ti guide fabrication after Er doping and because adjustments would continually need to be made to the recipe, Focused Research performed the Ti indiffusion at its facilities instead of subcontracting this work to UTP as proposed in previous quarterly reports. The new diffusion conditions for the Ti diffusion will effect the properties of the acoustic waveguides which must be fabricated in an earlier step. In order to avoid confusion between effects produced by the Er doping in the LN and effects caused by changes in the acoustic waveguide AOTFs were processed using unguided acoustic waves.

The AOTF device fabrication began with the preparation of five LN wafers for the lithography process. Two of the wafers were undoped LN and three wafers doped with Er. The undoped wafers would act as control samples to check the waveguide fabrication process and determine the effect of the Er dopant. The masks required for formation of the waveguides and for patterning of the electrodes used to excite acoustic waves were provided to Focused Research by D. Smith. The lighography proved challenging and was performed a number of times until at least one Er doped and one undoped wafer was successfully patterned with Ti. The diffusion was performed using the conditions determined in our earlier studies. Once the waveguides were fabricated they were inspected under the microscope and no microcrystallites were observed on the surface. Figure 4 shows optical micrographs of the waveguides formed using these diffusion steps.

Lithography was used to pattern electrodes on the surface of the LN wafer. These electrodes are used to excite the acoustic wave in the AOTF device. The electrodes were composed of 100 Å of Ti to provide adhesion to the LN surface followed by 500 Å of Au to provide adhesion to the gold bonding wires used to connect to the electronic circuit. With all the lithography steps completed the wafers were diced into 1 cm by 4 cm pieces and the edges were polished to provided for launching onto the waveguide.

The final AOTF devices were mounted individually in a protective metal housing and electrically connected to a 100nH matching circuit to excite the acoustic waves in the AOTF. The package provided standard SMA electrical connectors to allow simple connector to lab equipment.

Four devices were delivered to D. Smith in January 1997 for theoretical and experimental studies of the filter transmission function of the pumped AOTF to be performed. Other investigations include amplifier-related issues such as saturation power, noise figure, signal-to-noise ratios, and system performance will be carried out at CWRU.. Two of the AOTF devices were Er doped to provide gain and two of the devices were undoped to provide for comparison and testing of the AOTF function without Er.

Conclusions

The purpose of the investigations carried out by Focused Research was to address concerns about the use of AOTF devices in practical systems. These issues include robustness, packaging, insertion loss and insensitivity to input polarization and temperature. Focused Research successfully completed all of the technical objectives of the contract.

In the first part of the contract the issues of packaging robustness and insensitivity to input polarization and temperature were addressed. Through this contract Focused Research was able to demonstrate the suitability of the standard AOTF devices, manufactured by its parent company New Focus Inc., for practical system integration. The fabrication of polarization-independent AOTFs with temperature control demonstrated that it was possible to manufacture devices insensitive to both input polarization state and temperature.

The second part of the contract investigated the doping of the host crystal with Er to provide optical gain. The two stage diffusion process required to first dope the host crystal and then to produce optical waveguides provided a number of technical challenges. Incorrect diffusion conditions resulted in an interaction between the Ti and Er dopants which produced high propagation losses. We concluded that these losses were due to the formation of secondary phase compounds which disrupted the crystal surface. Focused Research determined the appropriate conditions required to successfully perform the double diffusion process and demonstrated gain in the optical waveguides. AOTF devices doped with Er were supplied to the other members of the contract team. A full discussion of the performance of the AOTF devices fabricated by Focused Research under this contract will be given by Dave Smith of Case Western Reserve University, in the full report.

The AOTF is a versatile device with many potential advantages in optical systems. The advanced AOTF device fabrication studies carried out under this contract have given us a firm understanding of the critical device fabrication issues. It has also overcome the

device limitations which had previously precluded the use of AOTF technology in practical systems. Several large consortia including the DARPA funded ONTC testbed have tested this AOTF technology in their networks. We are confident that the AOTF will be a key component in the fiber backbone of future transparent optical networks and that scaleable wavelength-division-multiplexed (WDM) systems will play an increasingly important role.

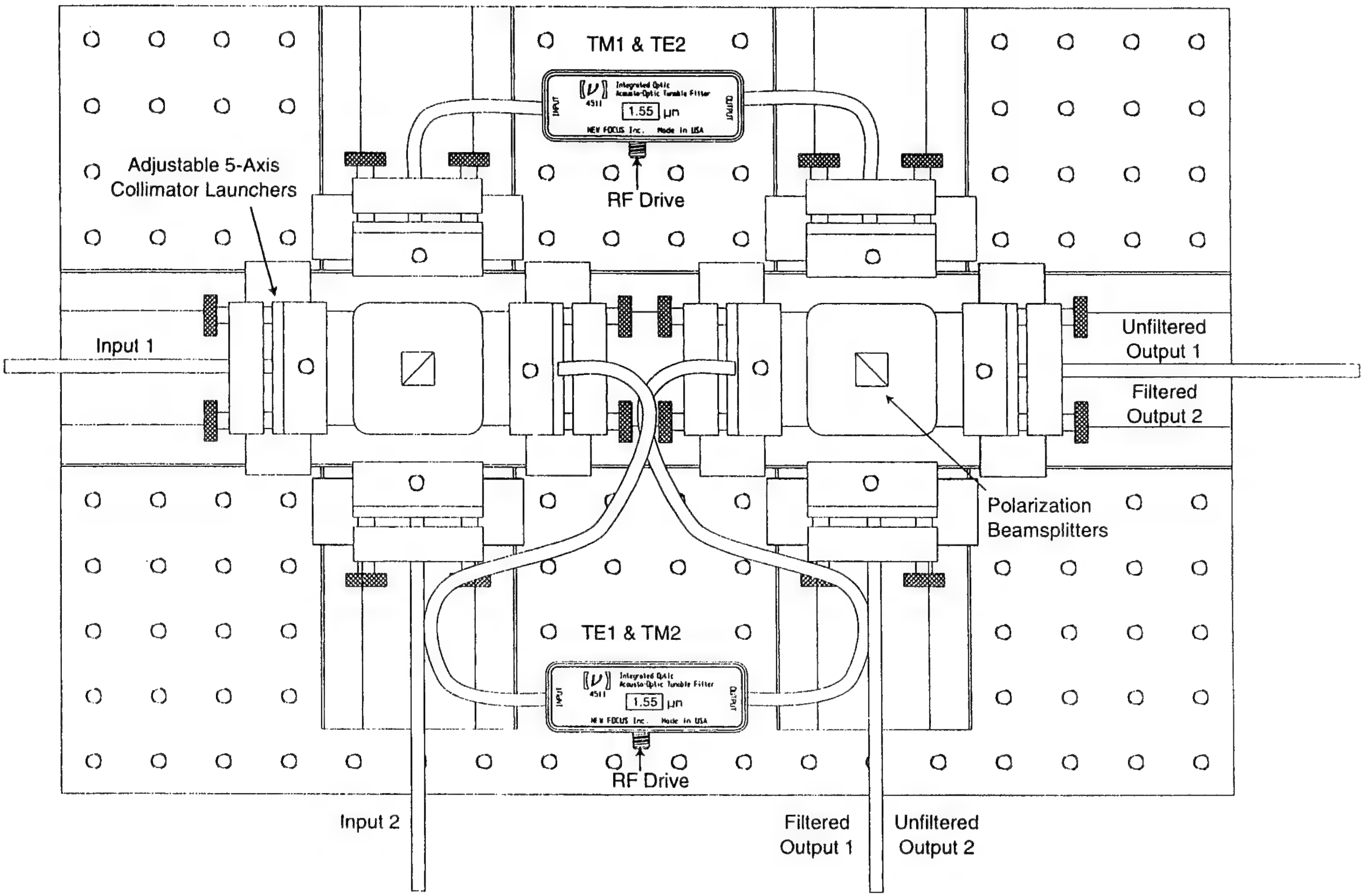

Figure 1. Polarization insensitive AOTF module.

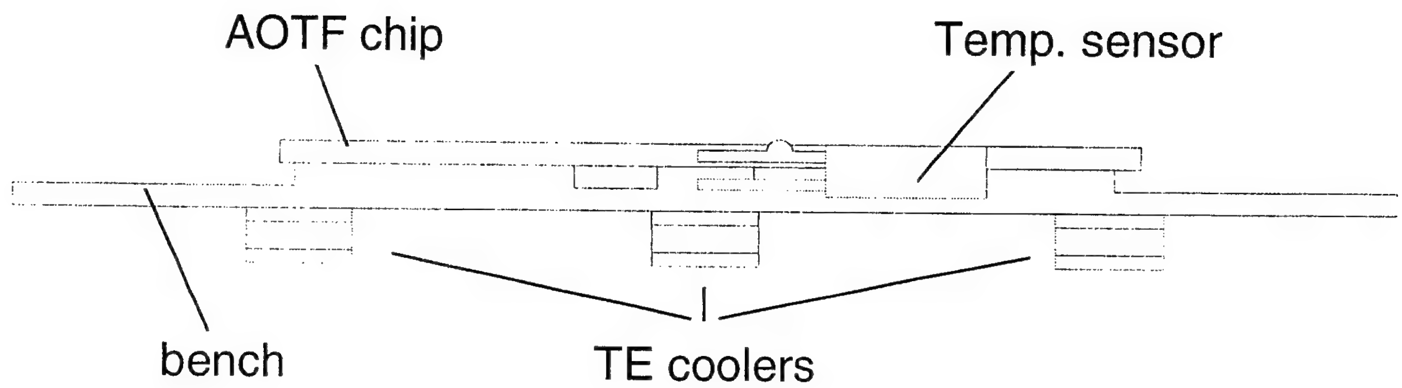

Figure 2. Thermoelectrically cooled AOTF package design.

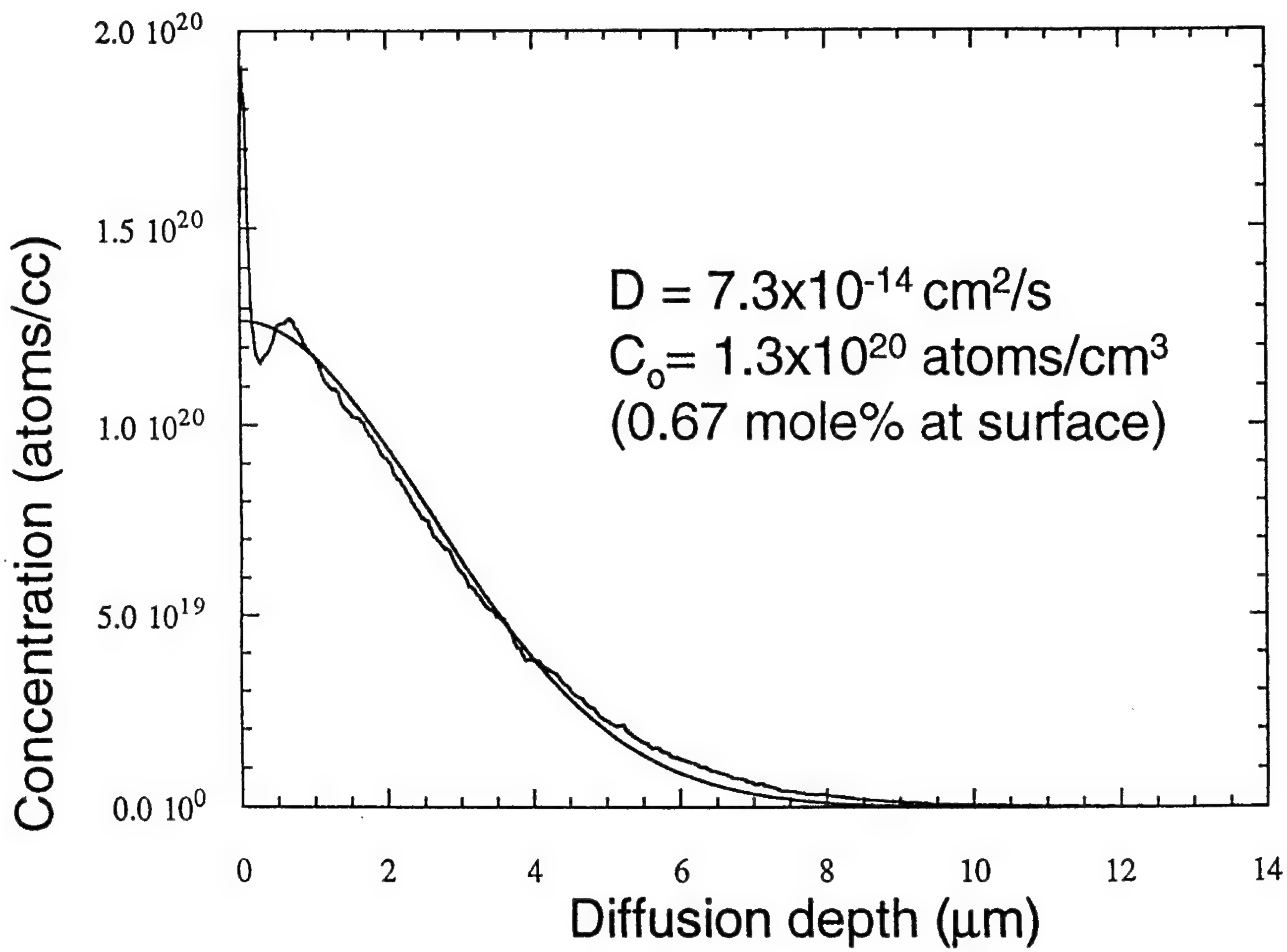

Figure 3. SIMS analysis of 100 hour Er diffusion into $LiNbO_3$.

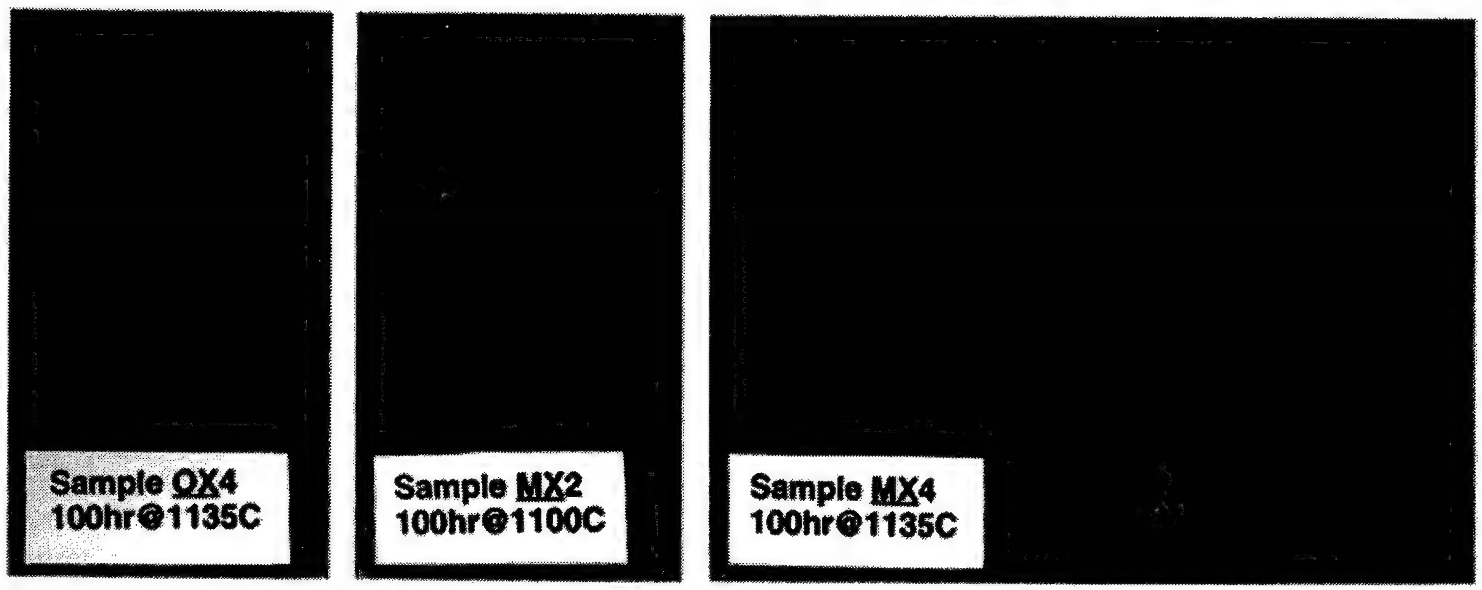

Figure 4. Optical micrographs of Er diffusion into $LiNbO_3$.

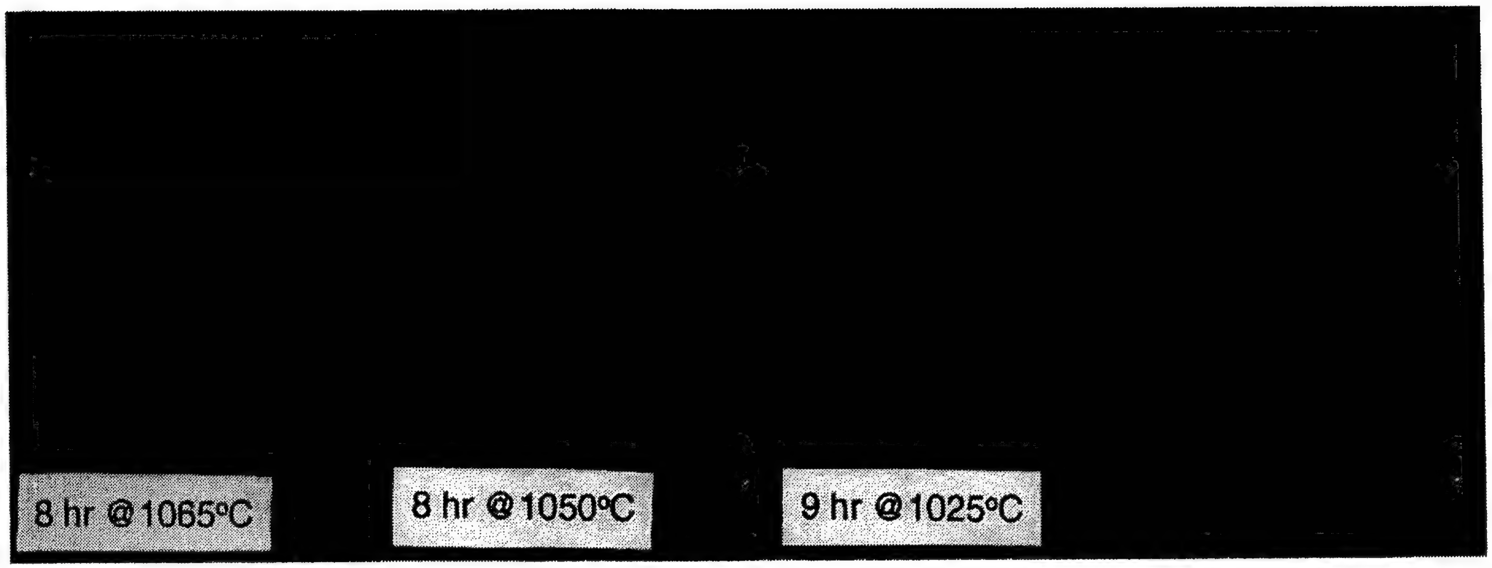

Figure 5. Optical micrographs of Ti diffusion into Er:$LiNbO_3$.

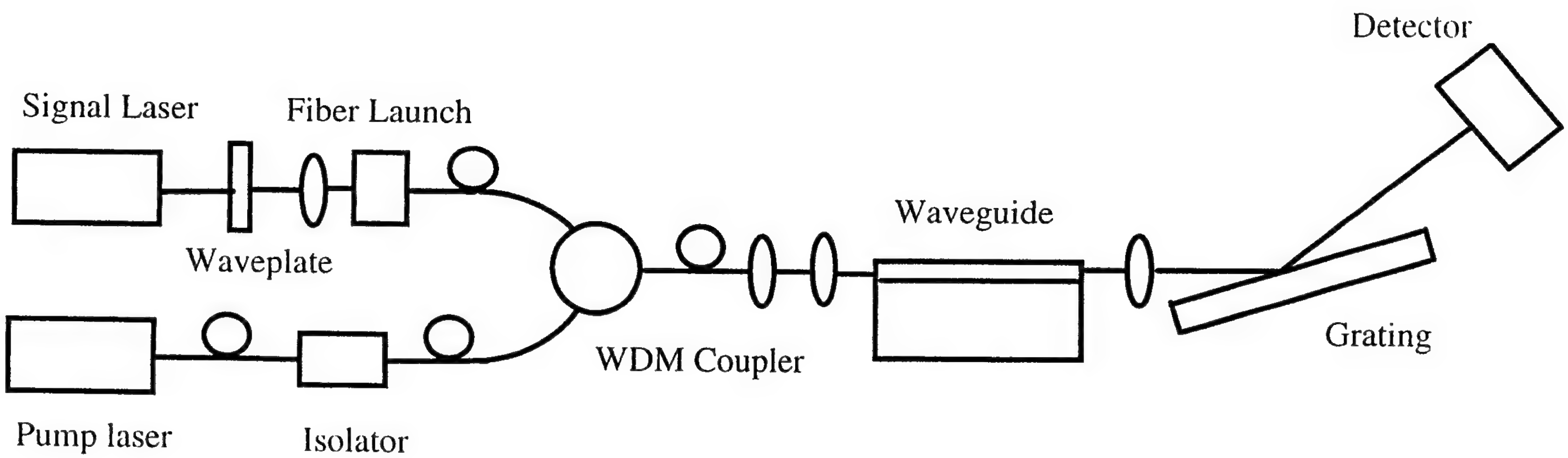

Figure 6. Experimental arrangement used to measure the gain in Er:LiNbO3 waveguides.

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